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FIELD TEST OF A THERMAL ACTIVE BUILDING SYSTEM (TABS) IN AN OFFICE BUILDING IN DENMARK

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ABSTRACT

An increasing attention has been addressed in the last years to the assessment, at the same time, of energy performances and indoor environmental quality in buildings. Focusing on thermal comfort recent international standards as ISOEN7730 and EN15251 introduce criteria for using categories in the indoor environmental assessment of a building. At the same time, also use of low temperature heating and high temperature cooling systems in non-residential buildings has increased, due to the energy efficiency and the economical cooling and heating performance of this kind of plants.

This paper presents an experimental study in an office building in Denmark where cooling in summer is provided by thermally activated building systems (TABS). Indoor climate quality evaluation, cooling system performance and energy consumption for a specific room were analyzed with different levels of internal gains. The experiments were carried out monitoring air and operative temperature, relative humidity and CO_2 levels in the room where internal heat gains from people where controlled and simulated by heated dummies positioned at the same workstations used by employees during the workdays. Supply and return water temperature in the pipes of the hydronic system, and energy consumption of the chillers were monitored. The performance of this test room was also analyzed by the dynamic building simulation tool Energy Plus.

The paper includes a comparison between experimental collected data and simulation results. Besides the paper show example on how to present data from long-term measurements or simulation results.

INTRODUCTION

Interest in low temperature heating and high temperature cooling systems in non-residential buildings has increased in the last years. The reason of this attention is due to the high energy efficiency and the cost reductions achievable with this kind of systems. These systems are characterized by the pipes, embedded in the structural concrete slabs of multi storey buildings (Babiak et al., 2010), in order to get more mass and thermal capacity (De Carli et al.,2003). According to (Olesen et al., 2006) different system configurations based on the building thermal storage activation are called TABS (Thermo-Active Building System). Slabs are thermally activated by water or air (Feustel and Stetiu, 1995. Santamouris and Asimakopoulos, 2006. Braun, 2003) that operate with small difference between room air and HVAC system temperature allowing the use of low temperature heat sources (Olesen, 2000). Except for this thermal storage effect, the TABS design is based on the same parameters characterizing other radiant systems (spacing and diameter of the pipes, thickness of concrete layer, water temperature, water mass flow rate) (Olesen, 2000. Haase and Anderson, 2007). The high water temperature for cooling shows an overall energy consumption lower than conventional air conditioning systems and offers the possibility of using renewable or recovery sources of energy, or technologies not usable in traditional systems. Ventilation combined with TABS appears to be very promising alternative to conventional all-air system even for continental climates, offering both significant primary energy savings as well as thermal comfort advantages (Henze et al., 2008). In fact the ventilation systems are here designed to provide only standard-requested amount of fresh air, to remove latent loads and to supplement in peak hours, while thermal loads can be balanced using TABS. For this reason, the ducts size of the ventilation system can be smaller and suspended ceilings are not needed. (Pfafferott et al., 2007) Talking about passively cooled low-energy office buildings, in moderate European summer climate a good thermal comfort can be provided removing heat loads only by TABS using ground cooling and/or night ventilation. Moreover this kind of system allows to remove the daytime peaks loads during the night time, when the prices of electricity are lower (Rijksen et al., 2010), and to use water temperature in the pipes close to desired room temperature. It is important to highlight that operative temperature drifts in the room can be expected because it cannot be controlled as a fixed level (Olesen, 2000). Significant energy saving can be achieved using adapted system topologies and applying appropriate control solutions for TABS (Lehman et al., 2011) (Lehman et al., 2007).

Examples of TABS application in architectures are described in (Henze et al., 2008) and in (Babiak et al., 2007). In literature studies about performance of the systems, controls and thermal comfort are mainly conducted through simulations tools, like TRNSYS and Energy Plus (Olesen, 2000) (Babiak et al., 2010) (Lehman et al., 2011) (Lehman et al., 2007). In particular in (Henze et al., 2008) primary energy and comfort performance of ventilation assisted thermo-active building systems, relative to a conventional all-air system in a compact office building, are compared. In (Fellin and Sommer, 2003) simulation with TRNSYS and CARM are conducted for a building located in two different countries, with two different strategies of ventilation and two possibility of systems, with good results for comfort conditions in both heating and cooling season. In (Gwerder et al., 2008) a method for dimensioning and for automated controls of TABS is proposed with the support of dynamic simulations.

In some cases long term measurements are performed to calibrate and validate the simulation model (Kalz et al., 2007) (Tian and Love, 2009). In other cases, the model supports the measurements in the evaluation of thermal comfort and energy performance of HVAC (De Carli et al.,2003). Only in very few studies is the performance of a TABS system evaluated mainly by measurements (Zimmermann and Andersson, 1998).

Aim of the work is to evaluate the TABS performance through field test in a real office building, using simulations tools in the start-up and in the final phase of the process to support the investigations. The study consists in the assessment of the TABS hydronic system at the variation of internal loads in summer.

METHODS

The field tests took place during summer 2011, in an open plan office that was part of a bigger office building situated in Denmark. Heated dummies and heaters were positioned at the same workstations used by employees during the workdays, and located homogeneously in other empty areas of the room, with the aim to simulate internal gains from people, computers and other sources. During the experiments, dynamic simulations performed through energy simulation tools were conducted simultaneously with physical measurements. The entire investigation process can be divided in four different phases, deepen described in the "Experiment description" paragraph.

Case Study

The office is a 5380 m^2 building situated in Denmark (Lat: 55.5°, Lon: 9.75°). Most of the building areas are occupied by bank offices, while some rooms have been designed in order to be rented to external activities. The building is structured in three different levels. On each floor also single offices, meeting rooms and other rooms for dedicated services are placed. The building envelope is made mainly by structural glass, with thermal transmittance U=1.1 [W/m^{2}K], and with the transmission coefficient (visible light/solar energy) equal to [0.64/0.35]. The offices are normally occupied during daily time from 8:00 to 18:00, from Monday to Friday. Thermal and air quality in the building are guaranteed by a different combination of systems. Heating in winter is provided in part by convectors, and in part by an hydronic system (floor heating), while cooling in summer is given in part by an hydronic system (floor cooling) and in part by TABS (for South-West exposed offices). Also the ventilation system, in addition to air quality control, contributes to add or remove peak loads respectively in winter and summer period, in some part of the building. The ventilation is natural in large open spaces, and mechanical in meeting rooms and single offices.

The specific investigation has been performed in one selected room of the building, situated at the first floor, of which a schematic representation is shown in Figure 1.

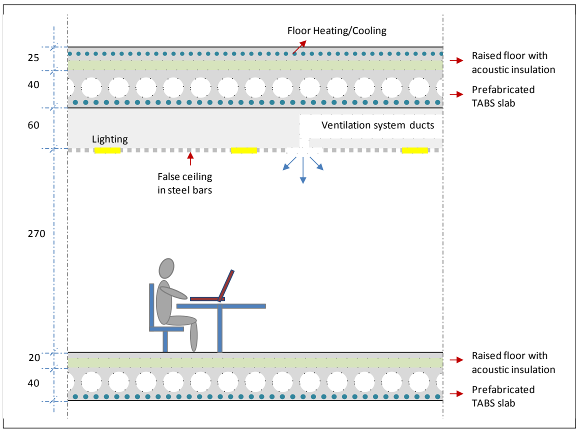

Figure 1- Scheme of the analyzed room.

This room has a South-East exposure, and the floor surface is equal to 268 m^2. In winter time heating is guaranteed by convectors, located on the floor along the façade, and balanced by mechanical ventilation. In summer a thermal active building system integrated in the ceiling, combined with mechanical ventilation, provides to cool the environment. Both the floor and the ceiling slabs of the room have a raised floor with acoustic insulation, and pipes embedded in the lower part of the concrete slab. A floor heating/cooling is situated in the upper layer of the ceiling slab, with the aim to heat/cool the room above. The lighting level in the room is controlled by sensors of presence and the intensity of the artificial lights is balanced with the natural light. There are automatic and manually curtains for solar radiation control, and the employees have the possibility to open/close the windows.

Even if one of the characteristics of the TABS is that it allows to avoid the suspended ceiling (Haase and Anderson, 2007), in this case a suspended ceiling made in steel bars, distant 60 cm from the slab, integrates the light and hides the ducts of the ventilation system.

Experiment description

Phase 1: Experiment set up condition

In order to determine the level of heat gains to install in the examined room, dynamics simulations were performed with the support of the energy simulation tool TRNSYS (16.1.0003). The use of simulations in the first phase of the process allowed to solve the energy balance of the room in cooling mode, giving as outputs the operative temperature and the total internal gains to insert in the room, with the scope to reach different levels of internal loads. Through the simulation model, it was possible to introduce different levels of internal gains in the room by adding people and computers in the office. Moreover, TRNSYS allowed to simulate the TABS system setting the inlet temperature in the pipes as a constant value. For these simulations the temperature was fixed 18°C, according with the data monitored during the days before the experiments. The objective of the simulations was to estimate how many dummies (1 dummy = 1 person + 1 computer = 170 W) had to be placed in the room to reach high levels of cooling load in the room.

During this first step of simulation, the office was modeled simplifying the room shape as a rectangular based room (14m x 19m), high 3.30m. Two of the four walls of the room were external walls, South and East exposed. The U value of the windows was set 1.1 W/m^{2}K, while the U value for the walls was set 0.2 W/m^{2}K. The relationship between transparent and opaque surface was 0.4. The other two perimeter walls, the floor and the ceiling were considered adiabatic.

Simulations were performed considering:

- Artificial lights: regulated according with the solar radiation
- Ventilation system (total flow rate: 3.6 ach - estimated from design documentation, air supply temperature: 20°C - average value estimated from the data collected through measurements performed in May)
- TRNSYS weather file for the city of Copenhagen.

Simulations have been performed considering the ventilation system always on and people in the room for 24 h a day, because it was decided to carry out experiments also during night time and with the ventilation system always on. In this way it was possible to evaluate the level of internal load that it was possible to reach without solar radiation.

Simulations were performed for sunny and cloudy days of August. In fact, in case of field measurements, where the boundary conditions could not be controlled, a preventive evaluation was necessary in case changing of the experiments setting were needed, according with the weather condition, when measurements were already running.

Phase 2: In field measurements

Measurements were carried out in the selected room from August 13 to August 16, 2011. During these experiments different levels of internal loads were inserted in the office, according with outside weather condition and based on the results from the simulations. Therefore different scenarios of analysis were considered during the tests. These settings were three, and were characterized by the introduction of internal gains as it follows:

- First Scenario (S1) - 30 dummies (5,1 kW) and 3 heaters (3 kW)
- Second Scenario (S2) - 30 dummies (5,1 kW)
- Third Scenario (S3) - in addition to the 30 dummies (5,1 kW), in the room there were 11 people with 11 computers (1,9 kW).

Because of the limited number of available dummies, and because of the absence of solar radiation, in S1 the heat gains were increased by inserting heaters.

During the tests, physical parameters (Table 1) were collected in the room through the use of a stand positioned in the center of the room, on which different kind of sensors were located at different heights. Then, operative temperature and surfaces temperatures were also collected in different points of the room. At the same time a weather station was logging data about the outside environment, and sensors of temperature were measuring temperature of the fluids in the systems. All the monitored parameters, the typology of sensors, their position, and the frequency of acquisition are listed in Table 1.

Note: during the experiment the floor cooling of the room above the tested one was not working.

Results of the monitored parameters

Outside weather conditions, temperature profiles, and operating of the cooling and ventilation systems during the experiments are shown in this paragraph.

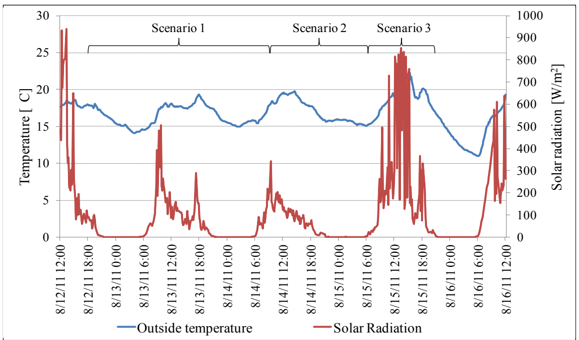

Figure 2 –Outside temperature and Solar radiation during the days of experiments.

Table 1. Monitored parameters during experiments.

Parameter	N. of probes	Position of the sensors	Instrument	Acquisition Frequency
ENVIRONMENT IN THE ROOM				
Operative Temperature [°C]	4	Homogeneously distributed in the room, at the high of 110 cm	Gray globe sensor	10 minutes
	4	Positioned on one stand in the center of the room, at 4 heights: 10 cm, 60 cm, 110 cm, 170 cm	Gray globe sensor	1 minute
Air Temperature [°C]	1	Installed attached to a wall, in a central position of the room, at the height of 170 cm	Thermoresistance (permanent)	10 minutes
	4	In the center of the room, at 4 heights: 10 cm, 60 cm, 110 cm, 170 cm	Thermoresistance	1 minute
Air Velocity [m/s]	4	In the center of the room, at 4 heights: 5 cm, 10 cm, 20 cm, 60 cm	Anemometer	1 second
Surface Temperature [°C]	1	Different points of the room: windows, walls, floor, ceiling and suspended ceiling	Thermocamera	3 hours (if possible)
Relative Humidity [%]	4	In the center of the room, at 4 heights: 10 cm, 60 cm, 110 cm, 170 cm	Anemometer	1 minute
CO_2 concentration [ppm]	1	Installed attached to a wall, in a central position of the room, at the height of 170 cm	CO_2 sensor	10 minutes
OUTDOOR ENVIROMENT				
Air Temperature [°C]	1	Installed on a Weather Station positioned outside the building	Thermoresistence	10 minutes
Relative Humidity [%]	1		Psycrometer	10 minutes
Wind Speed [m/s] and Direction [deg]	1		Anemometer	10 minutes
Solar radiation [W/m^2]	1		Solarimeter	10 minutes
SYSTEMS				
Supply Air Temp. in the ventilation system	1	Positioned in a diffuser of supply air in the centre of the room	Thermoresistence	10 minutes
Return Air Temp. in the ventilation system	3	Positioned in ducts of exhaust air in different points of the room	Thermoresistence	10 minutes
Opening of the dumpers	8	Situated in proximity of the dumpers in the supply and exhaust ducts of the ventilation system	Opening dampers sensor	10 minutes
Supply Water Temp. in the TABS	1	Positioned in the supply water pipe at the beginning of the room circuit	Thermoresistence	10 minutes
Return Water Temp. in the TABS	1	Positioned in the return water pipe at the end of the room circuit	Thermoresistence	10 minutes

Figure 2 shows the solar radiation and the outside air temperature collected by the weather station. The graph also illustrates the three scenarios. During S1 and S2 the solar radiation was really low, while it was higher, but discontinuous, in the third scenario. The average outdoor temperature raised of about 2°C each day during the day time. In the analyzed room, as it can be seen from Figure 3, the ventilation system started to run in the middle of S1 (at 18:00), and from that moment the supply water temperature in the pipes fluctuated between 15 and 19°C. The temperature in the room was set as 23°C. The ventilation system was working in S1during the day time, with little flow rate, and supply air temperature 23°C. It was switched off during S2, and switched on again during S3. In the beginning of S1 both ventilation and TABS systems were not working. During the day just the ventilation system was cooling, and then in the night just the TABS system was operating. In S2 the cooling was only provided by TABS. While in S3 both TABS and ventilation systems were working together.

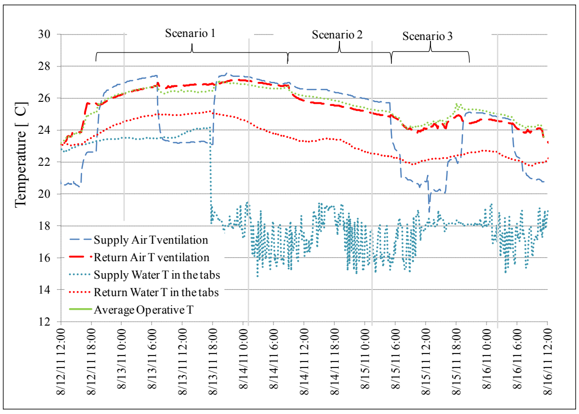

Figure 3- Temperature profiles of average operative temperature in the room, supply and exhaust air temperature in the ventilation system and supply and return water temperature in the pipes.

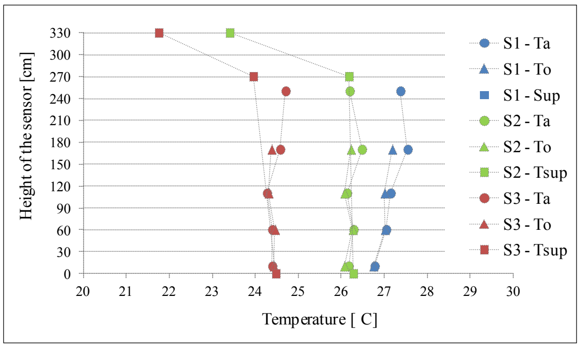

Figure 4- Average air, operative, and surfaces temperature in the room, for the three scenarios.

Figure 4 shows, together with the average air (Ta) and operative (To) temperature, the average surfaces temperature (Tsup), measured with the infrared camera, of floor, ceiling at 270 cm (suspended ceiling) and ceiling at 330 cm (concrete surface). While floor and suspended ceiling temperatures were in general really close to the air temperature in the room (almost constant at different heights in all the scenarios), ceiling temperature differed of at least 2°C from the air temperature, when the system was operating. The surface temperatures of the floor denote that the tabs integrated on the ceiling of the room below (ground floor) were not removing any significant load from the analyzed room. The average values showed by the graph represent a time interval where temperatures were almost constant, and the systems were working. During S1 the interval represents a period of night time in which surfaces temperatures could not be collected.

Phase 3: Calibrated dynamic simulations and cooling loads determination

The aim of this phase was to evaluate the real cooling load in the room during the experiments. For to reach this objective, the tool Energy Plus has been used for performing calibrated energy simulation. The choice of employing Energy Plus instead of Trnsys it has been dictated by the fact than Energy Plus has been considered more suitable for to make a realistic simulation models. This time the room has been modeled exactly as it was in reality, without simplify any geometry. Also the shape of the windows, slanted in some points, was modeled with precision with the aim to evaluate the right heat gain entering in the environment during the daily hours. At this aim, the first calibration of the model consisted in the implementation of monitored weather data in the Energy Plus weather data file used in the simulations. In particular, this monitored data correspond to the parameters logged by the weather station described in Table 1. The range of supply water temperature in the hydronic circuit was set, according with the monitored data, from 16°C to 18°C, and the hours of the system operating were set as they were during the experiment. The ventilation system was also set for working as in reality, setting the flow rate 1.4 kg/s during S3, and with an average inlet temperature between 20°C and 22°C. The room setpoint temperature was set 23°C.

The simulation model has been validated through the comparison with the experimental data. Coherency in the results has been verified in terms of time profiles of the attended behaviors. Results and further information are shown in (Raimondo, 2012). Knowing supply and return water temperature in the TABS system, and flow rate in the pipes, the loads removed by the TABS, called water loads (Causone et all., 2010) were calculate by using the basic equation:

$$Q/A = m*cp*DT \qquad (1)$$

Where:

m = flow rate in the pipes

Cp = specific heat of the water

DT = return and supply water temperature difference in the pipes.

In the calculations, the flow rate in the pipes was set at its nominal value, equal to 0.42 [l/s].

Figure 5 shows both the profiles of the cooling loads in the room and the water loads. As we do not have steady state these two values may not be equal.

During S1 the TABS were not working, the internal loads in the room exceeded 40 W/m^2 and the temperatures in the room increased (except when the ventilation system was operating). During this time, the slab accumulated a lot of heat that began to be removed by when the TABS started working. Supply temperature in the circuit was in the beginning about 18°C, and then started to fluctuate between 16°C and 18°C. During the normal working days (of summer), over the experiments, the temperature in the room is usually between 22°C and 23°C, and the supply water temperature in the TABS is around 20°C. At the end of S1 the difference of water temperature between supply and return reached 8°C, and the cooling loads removed by the system on the water side reached 60 W/m^2. This was due to the heat stored in the concrete slabs.

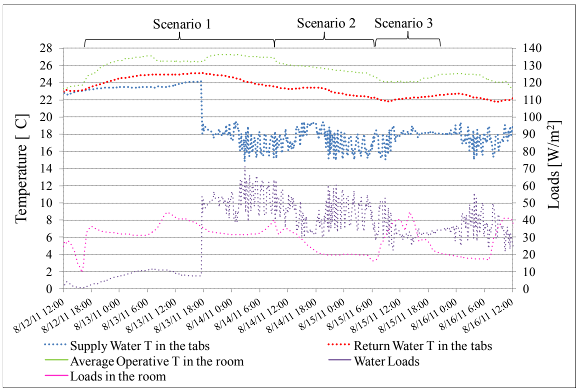

Figure 5- Profiles of Operative temperature, supply and return water temperature, water loads, and heat loads in the room

During S2 the loads in the room were reduced, and also the water loads reduced. The room operative temperature, between the beginning and the end of the scenario, decreased of about 2°C. Same trend was for the return water temperature in the pipes, while the supply water temperature kept constant as it was in S1. During normal working days return water temperature is almost equal to operative temperature, while during the experiments the ΔT was always about 2K.

During S3 also people were in the room together with the dummies. Both TABS and ventilation system were working together: ventilation system contributed to remove loads from the room. The temperature in the room decreased at 24°C and the supply water temperature in the pipes was almost constant around 18°C. Considering that the air temperature set point was 23°C, for to reach lower temperatures in the room, in case of high thermal loads in the room, the supply water temperature in the TABS needed to be reduced.

Phase 4: Critical analysis of the results

In order to evaluate the performance of the cooling system, three different configurations, one for each scenario, were analyzed during the system operating time. These configurations represent an instant of the scenario, and a scheme of these configurations is illustrated in Figure 6.

Average values of measured parameters in the three configurations are listed in Table 2. From the data it is seen that the outside temperature increased from scenario 1 to 3, while the indoor air temperature decreased. This explains the higher losses for transmissions through walls and windows, and infiltrations, of S1 respect to S2 and S3.

Table 2- Measured temperature in the tabs system, in the ventilation system, in the room and outside.

Scenario	TABS				Ventilation				Average temperatures		
	Supply [°C]	Return [°C]	DT	Flow rate (kg/s)	Supply [°C]	Return [°C]	DT	Flow rate (kg/s)	To [°C]	Ta [°C]	Tout [°C]
1	18.1	24.7	6.6	0.42	27.4	27.1	-0.3	no	27.0	27.1	16.1
2	18.1	23.4	5.3	0.42	26.5	25.7	-0.8	no	26.1	26.1	18.8
3	17.9	22.1	4.2	0.42	20.5	24.1	3.6	1.4	24.3	24.2	19.6

For radiant systems a large part of the heat transfer between heated/cooled surface and room is by radiation, which can be highlighted by comparing the radiant and convective transfer coefficients (Perino, 2008) (Causone et al., 2009). From (EN 15377-2:2008) the approach to calculate a combined heat transfers can be expressed as:

$$Q/A = (hc+hr)*DT \qquad (2)$$

Where:

$(hc+hr)_{floor} = 6\ W/m^2K$
$(hc+hr)_{ceiling} = 11\ W/m^2K$
DT= difference of temperature between the average air temperature in the room and the surface temperature.

With this method, in addition to the already calculated water loads, also the loads removed instantaneously from the room by the cool ceiling surface, so called surface loads (Causone et all., 2010), were determined.

Results of all the analysis can be summarized in the schemes of figure 6.

During the configuration of S1 surfaces temperatures were not collected. In this case, just the total heat gains in the room and water loads were determined. As already said, during the previous two days the hydronic system was not running, and the slab accumulated a lot of radiant heat that was afterwards removed during the following days. The operative temperature in the room was high, but this is explained by the fact that no system were working. From this interval of time the temperature started to decrease.

Standard EN 15251 (EN 15251:2007) defines ranges of operative temperatures for the thermal comfort evaluation through a classification. Categories go from I (best) to IV (worst). The upper limit of category III for summer period in offices is 27 °C. As it is possible to see from the temperature profiles of Figure 3 and Figure 5, during this scenario this limit has been exceeded.

During the instantaneous configuration of S2 heat gains in the room were still high. Surface loads were lower than water loads, because TABS continued to remove loads accumulated in the slab during the previous days. This fact demonstrates that during S2, the TABS, cooling the ceiling surface, were balancing the cooling needs of the room. The indoor operative temperature was around 26°C (upper limit of category II according with (EN 15251:2007). During all S2 the operative temperature was between 25°C and 26°C. This means that the comfort requests were respected, being that the building has been designed to be in category II of thermal comfort.

During the third configuration shown in figure 6, the ventilation was contributing to remove loads from the room. Results denote that the system was not removing instantaneously enough heat to compensate the load produced by introduced heat gains. Finally, the operative temperature was around 24°C, respecting category I of thermal comfort.

In order to analyze the performance of TABS, the water loads in the three configurations were calculated in relation to the difference between the average water temperature and room operative temperature. This is equivalent to the total heat exchange coefficient between water and room:

$h_{total} = L / [Top - (T_{supp} + T_{ret}) / 2]$ (3)

Where:

h_{total} = Total heat exchange coefficient, i.e. water loads for degree temperature difference between average water temperature in the circuit, pour square meter [W/m²°C]

L = Water loads , calculated with (1) [W/m²]

T_{op} = Operative temperature [°C]

T_{supp} = Supply water temperature in the TABS [°C]

T_{ret} = Return water temperature in the TABS [°C]

Results are shown in figure 7.

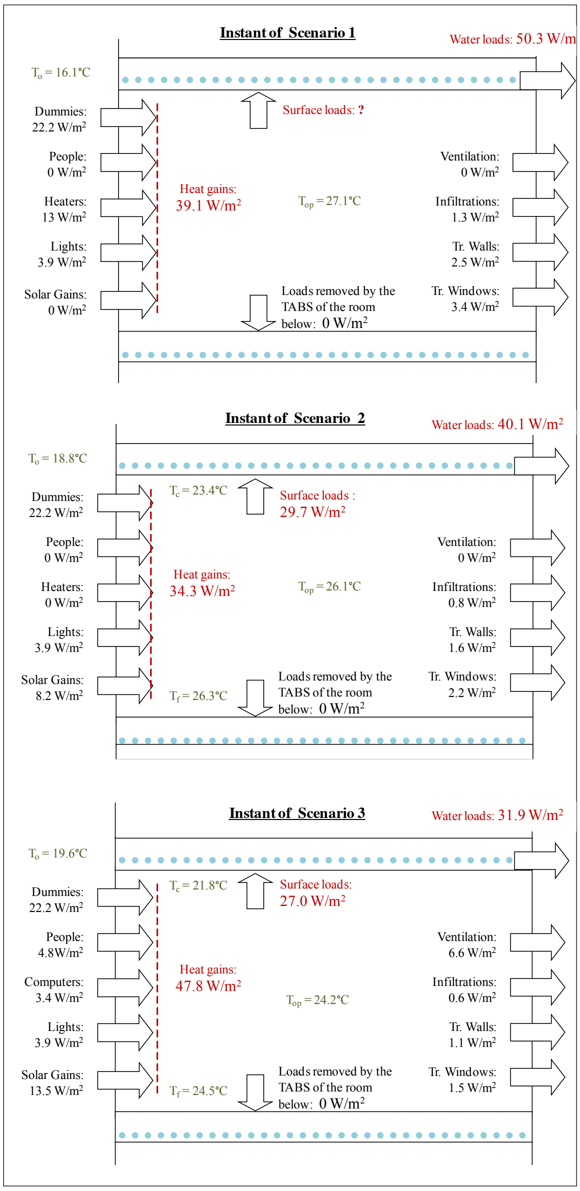

Figure 6 – Instantaneous configuration for the three scenarios.

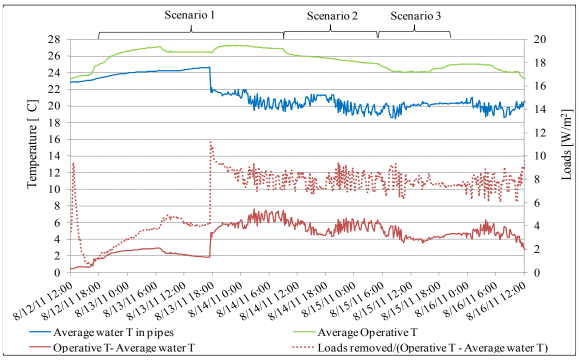

Figure 7 – Water loads per degree temperature difference between average water temp. in the pipes.

Figure 7 shows that the system removed averagely about 8 W/m² per degree temperature difference between average water temperature (cooling capacity = 8 W/m²°C), during all the scenarios. This means that also in case of different loads in the room, the system control allowed to maintain a good performance. The average water temperature in the pipes was always around 20°C, while the operative temperature decreased from S1 to S3. When for example the operative temperature was 26°C (S2), and consequently the temperature difference was 8°C, the system could remove about 48 W/m². Wanting to evaluate how much loads could be removed by the system at lower water temperature, if the average water temperature in the pipes in that case was 18°C, it could be said that the system could then remove about 64 W/m², but in that case the supply temperature would be too low (<18°C), which could increase the risk for condensation on the supply pipes and it would be more difficult to control. So a cooling capacity of 40-50 W/m² can be documented by the present test.

CONCLUSIONS

In this paper the performance (cooling capacity) of a Thermal Active Building System (TABS) was studied by field measurements supported by dynamic simulations. The following results were obtained:

- Support of dynamic building simulations is useful for designing a more accurate field test and for the analysis of the results, in particular in the determination of internal loads.
- The measurements show that under different scenarios the total heat exchange coefficient between the average water temperature and the room (operative temperature) was almost constant about 8 W/m² per degree temperature.
- The analyzed system could remove from the room a cooling load of 30 W/m² using an average supply water temperature in the pipes of 18°C. Higher cooling loads could be removed with lower temperature.
- The presence of the suspended ceiling did not interfere with the ability of the system to keep comfort in the room.

- Also with high level of loads in the room the hydronic system was able to keep the thermal comfort conditions. In particular when also the ventilation system was running. Employees that were working in the office during the third scenario confirmed that fact filling questionnaires.

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